ABSORPTION OF X-RAYS IN THE 20 TO 100 KILOVOLT ENERGY REGION

by

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INTRODUCTION

Nuclei may be excited by gamma radiation in two types of processes (4). The first type involves gamma energies sufficient to dissociate a heavy particle from the nucleus, which leaves the product nucleus either in the ground state or in an excited state. The second type of process concerns gamma energies insufficient for dissociation. The irradiated nucleus absorbs a photon in making a transition to a bound state and subsequently reverts to the ground state by a single or by a succession of gamma ray transitions. Each gamma ray transition has a definite probability of occurrance, λ, which is the reciprocal of the mean lifetime, τ, of the state for that energy. The mean life is dependent mainly upon the energy difference between two levels and the magnitude of the vector change in nuclear angular momentum, as may be seen from the equation for mean life (6)

$$\tau = \tau_o |\Delta \underline{I}|! ^2 \left(\frac{137}{E}\right)^{2|\Delta \underline{I}|+1} R^{-2|\Delta \underline{I}|} \quad \ldots\ldots (I)$$

where E = photon energy in units of $m_o c^2$

R = nuclear radius in units of classical electron radius

$\tau_o = 3.9 \times 10^{-21}$ seconds

$|\Delta \underline{I}|$ = magnitude of the change in nuclear angular momentum

Table 1 shows some approximate values for expected mean lives of gamma emission as appears in Halliday (6).

The magnitude, $|\Delta \underline{I}|$, of the vector change in nuclear angular momentum may have values ranging from the sum to the difference

Table 1. Approximate mean lives for gamma emission.

Gamma energy (mev)	$\|\Delta I\| = 2$	$\|\Delta I\| = 3$	$\|\Delta I\| = 4$	$\|\Delta I\| = 5$
1.0	2×10^{-13} (sec)	6×10^{-10} (sec)	3×10^{-6} (sec)	3×10^{-2} (sec)
0.20	5×10^{-12} (sec)	3×10^{-4} (sec)	7 sec	20 days
0.05	5×10^{-9} (sec)	4 sec	20 days	2×10^{5} (yr)
0.01	2×10^{-5} (sec)	80 hours	9×10^{4} (yr)	9×10^{12} (yr)

of the spins between two energy states. Suppose the nuclear spin changes from 5 to 3 during a transition, giving a scalar difference, $\Delta I = 2$. Then $|\Delta \underline{I}|$ may have the values 2, 3, 4, 5, 6, 7, 8. The smallest value $|\Delta \underline{I}| = 2$ will have the highest probability of occurrance.

Gamma emission processes may be classified as to multipolar order in terms of this value $|\Delta \underline{I}|$. If $|\Delta \underline{I}| = 1$, the transition is a 2^1 pole or dipole transition. If $|\Delta \underline{I}| = 2$, the transition is a quadrupole transition; $|\Delta \underline{I}| = 3$, is termed an octopole transition, etc. Transitions may be further classified as electric or magnetic. Parity change in a specific transition determines which of these types occur. These facts may be summarized in the form of Table 2 (6). These selection rules for radiative transitions result from the imposition on the theory that total nuclear angular momentum and parity be conserved for the system (nucleus + photon).

Nuclear states having a "measurably great" mean lifetime against gamma emission are termed metastable. Both the metastable state and the ground state of the same nuclide are termed isomers. Wiedenbeck (9) has devised a system for measuring nuclear energy levels which makes use of this metastable state in different isomers. In his work silver was irradiated by high energy x-rays produced by a Van De Graff generator. After a given exposure the generator was turned off, and a count was taken of the activity of the silver. Thresholds for the absorption of x-rays were observed at the following energies: 1.18, 1.59, 1.95, 2.32, 2.76 and 3.13 mev. From the energy of the

Table 2. Lowest allowed multipole order.

Parity change?	ΔI Even	ΔI Odd
No	Elec $2^{\Delta I}$ pole Mag $2^{\Delta I+1}$ pole	Elec $2^{\Delta I+1}$ pole Mag $2^{\Delta I}$ pole
Yes	Elec $2^{\Delta I+1}$ pole Mag $2^{\Delta I}$ pole	Elec $2^{\Delta I}$ pole Mag $2^{\Delta I+1}$ pole

emitted radiation and its half life, the energy diagram shown in Plate I was deduced.

While much work by Wiedenbeck and others has been done in which the absorption of high energy x-rays have been studied, in no instance has any previous attempt been made to observe the nuclear absorption of low energy x-rays.

Many elements, Co^{60m}, Se^{75}, Br^{80m}, Rb^{87}, Sr^{87}, Tc^{94m}, Pb^{100}, Ag^{109m} and Sn^{113}, exhibit transitions involving gamma rays of 100 kilovolts or less (8). These are of particular interest in that conventional x-ray equipment may be used in investigation of possible resonant transitions. Of the above elements, Ag, Rb, and Sr were readily available; and since they represent different mean lifetime groups, were selected for this experiment.

Ag^{109m} exists with an abundance of 48.1 per cent, exhibiting an isomeric transition of half-life 40.5 seconds and gamma energy .087 mev. Ag^{107m} has a corresponding metastable level at .093 mev., with a gamma transition of 44.3 second half-life (8).

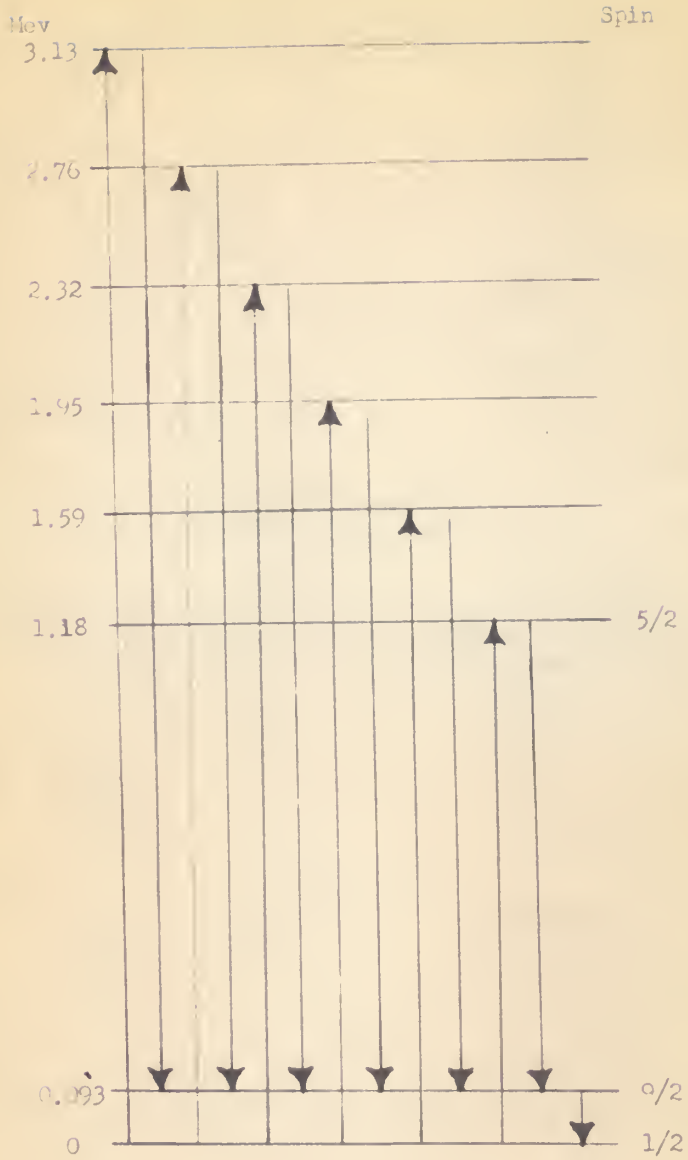
On the other hand, Rb^{87} undergoes β^- emission accompanied by gamma rays of .034, .053 and .082 mev. Whether in this decay scheme the β^- rays follow or precede the gamma emission is unknown. It was thus necessary to investigate both Rb^{87} and Sr^{87} for possible absorptions. Fortunately, both exist in nature, Rb^{87} with an abundance of 27.2 per cent and Sr^{87} with an abundance of 7.02 per cent.

It should be pointed out that the detection of possible

EXPLANATION OF PLATE I

Nuclear energy level diagram for silver showing the various transitions by which nuclei may reach the metastable state.

PLATE I



resonance absorption would have unlimited value in clarifying decay schemes of the above type and for determining which gamma ray transitions are to ground levels.

APPARATUS

The photon source was a Pickering x-ray unit capable of energies up to 100 kev. A Bragg x-ray spectrometer (Plate II) was constructed to select energies of the desired magnitude from the beam. A calcite crystal was mounted on the spectrometer table where it was capable of rotation to any desired angle. Near the bottom of the crystal was a small mirror with the plane of its face parallel to the crystal face. It was thus possible to use an optical lever system to determine the crystal's angle of rotation, θ, the relation being

$$2\theta = \arctan \frac{x}{y} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(II)}$$

where x = pointer reading on meter stick

y = 302 centimeters

The distance, x, was measured to .5 millimeter which indicated a possibility of measuring 2θ to .5 minute.

Attached to the goniometer arm was a Geiger tube which could be rotated to the angle, 2θ, where it intercepted the reflected beam. The angle, 2θ, could be measured directly to 1 minute and estimated to .5 minute on the goniometer.

For any setting of the crystal, the energy of the reflected

EXPLANATION OF PLATE II

Schematic diagram of apparatus

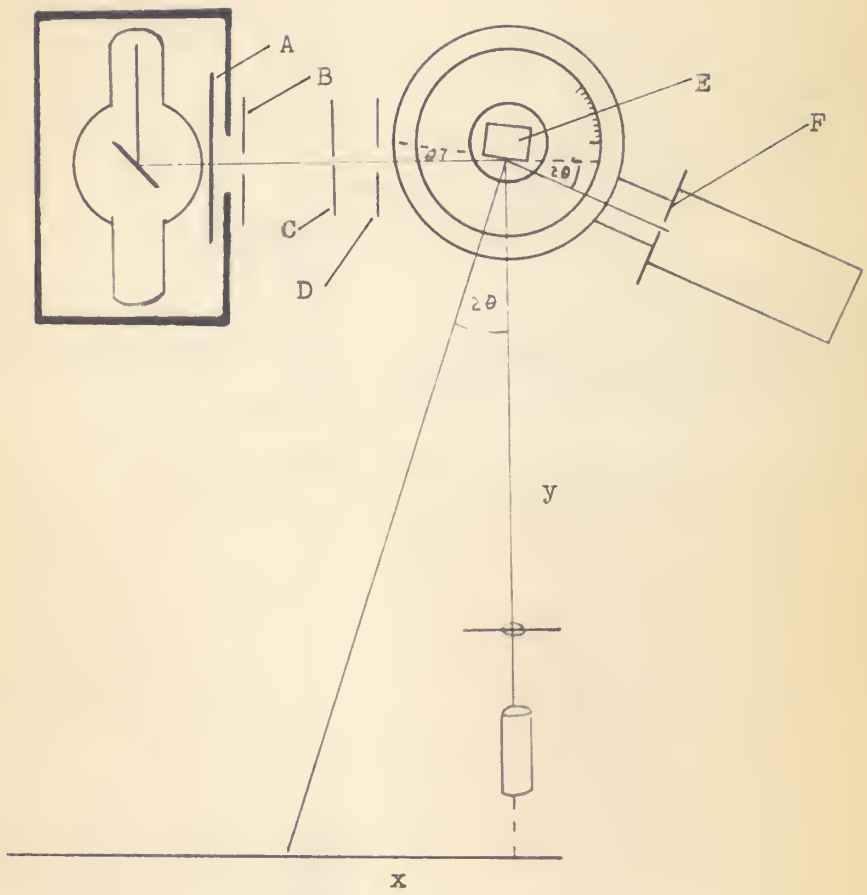
A - Metal absorber

B,C,D,F - Lead slits

E - Crystal

G - Geiger tube

PLATE II



beam could be determined from Bragg's relation

$$E = \frac{hc}{\lambda} = \frac{nhc}{2d \sin \theta} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(III)}$$

where E = energy of reflected beam in volts

hc = 12.395

d = 3.0290 $\mathring{A}$

n = order of reflection

θ = angle of rotation of crystal

A 5 mil lead collimating slit, B, was mounted directly in front of the x-ray tube. Slits C and D, 4 inches apart, had widths of 1 mil and 250 mils, respectively. Immediately in front of the Geiger tube was placed a fourth slit, F, of 1 mil width. The distance from the axis of rotation to both C and F was 25 centimeters.

A Berkeley scaler was used for determination of the counting rate. A loudspeaker attachment for the scaler was used in calibration procedures.

The resolving power of the spectrometer, $\frac{\lambda}{d\lambda}$, was determined from the curve shown in Plate III to be approximately 250.

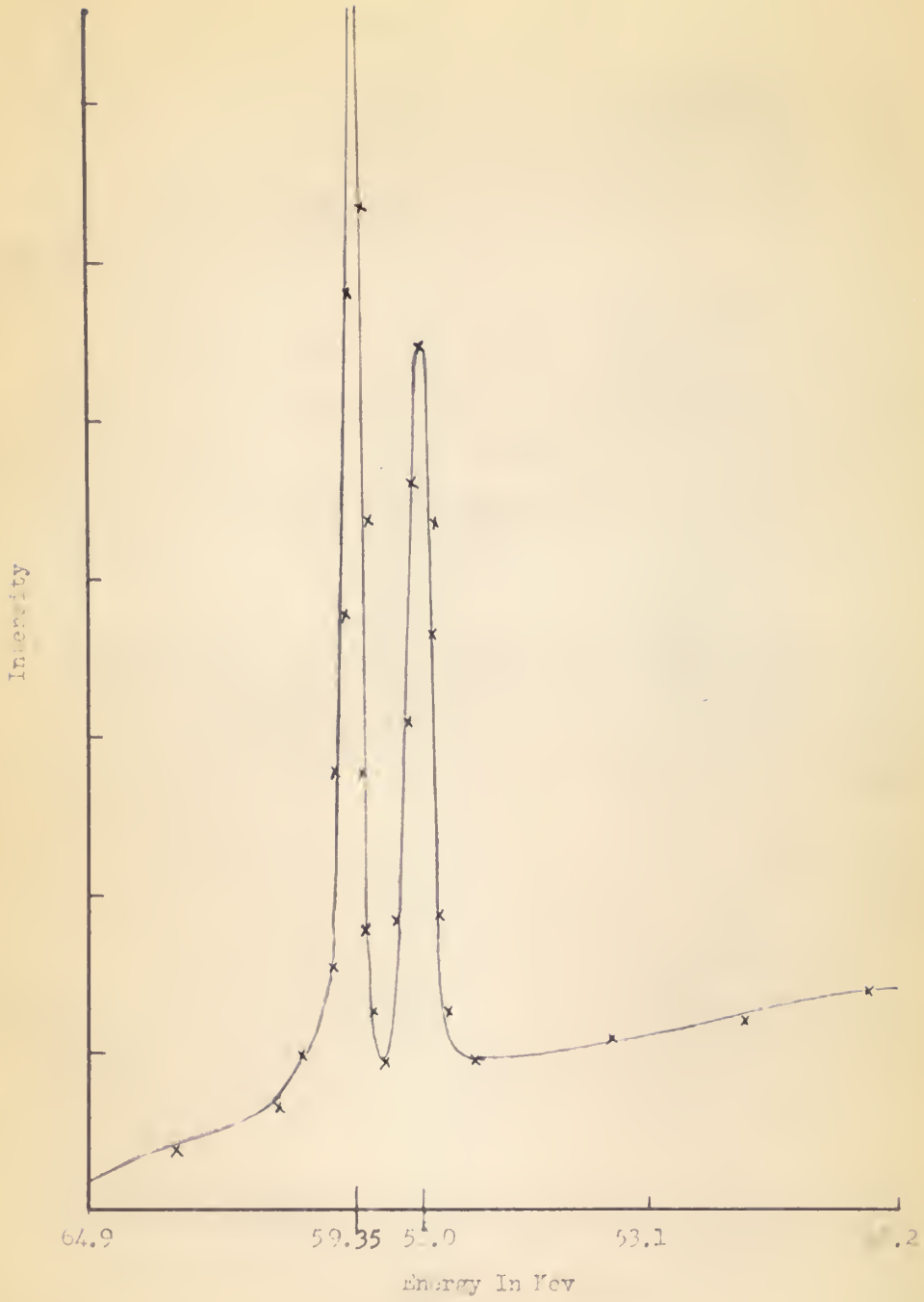
PROCEDURE

Calibration of the spectrometer was accomplished by utilization of the Kα characteristic lines of the tungsten tube target. This procedure was greatly facilitated by use of a loudspeaker attachment to the Berkeley scaler, since the

EXPLANATION OF PLATE III

A plot of the Kα characteristic lines of the tungsten tube target. The ordinate values of intensity were measured in terms of, $(I_o - I_b)$, the number of counts per minute, corrected for background.

PLATE III



variation in intensity of noise from the speaker gave an audible indication of counting rate. The zero reading of the goniometer scale was determined by removing the crystal table and rotating the Geiger tube into the direct x-ray beam to the point where the speaker gave maximum sound. Then the crystal and table were remounted on the spectrometer and the Geiger tube rotated to the angle, 2θ, calculated for the $K\alpha_1$ line. Next the crystal was rotated until the speaker gave maximum indication, which meant the crystal was approximately at the angle, θ. The zero of the meter stick scale was then found and by a series of minute alternate adjustments of Geiger tube and crystal the spectrometer was further zeroed in.

A very careful determination of background radiation was made and found to be 1.88 counts per minute.

After calibration, the general procedure was to set the spectrometer for a given energy, after which a series of counts were recorded on the scaler. Following this the absorber of the metal being investigated was inserted in the holder and another series of counts taken. Proceeding in this fashion, taking two series of counts at each energy, all desired energy regions were explored.

The equation for the absorption process is (3)

$$I_i = I_o e^{-ux} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (IV)$$

where I_i = number of counts with absorber in

I_o = number of counts with absorber out

u = absorption coefficient

x = thickness of absorber

Taking the log of both sides of equation IV, we have

$$u = \frac{1}{x} \ln I_o/I_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (V)$$

where the quantity I_o/I_i becomes $(I_o-I_b)/(I_i-I_b)$ when background corrections are made. The absorption coefficient, u, is independent of x for homogeneous x-ray beams and is assumed as such in the derivation of equation IV.

In order to determine whether any nuclear resonance absorption had occurred, graphs of $\ln (I_o-I_b)/(I_i-I_b)$ versus energy, E, were plotted over the energy regions explored for a given sample (Plate IV). Evidently, any rapid variation in absorption should show up as a sharp discontinuity.

The silver specimen was investigated in energy intervals of approximately .3 kev. over the region from 83.9 to 95.6 kev.

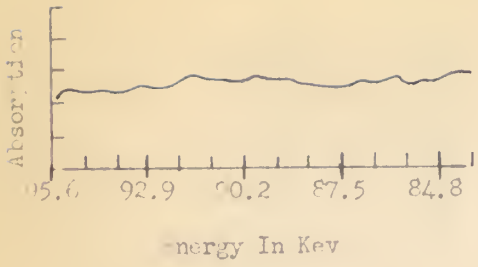
For the strontium sample the energy regions 33.6 to 34.5, 52.5 to 54.1 and 78.7 to 84.8 kev. were investigated. It was possible to investigate the rubidium only over the two highest of these last three regions. This was a result of the rubidium being enclosed in a quartz ampule which cut the counting rate down to a value very little above background at the lower energy range.

EXPLANATION OF PLATE IV

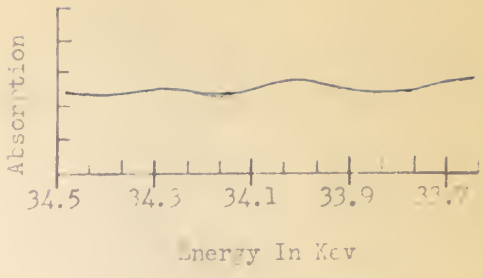
Absorption curves for Ag, Rb, and Sr. Each curve represents an average of data from three separate runs. Absorption was measured in terms of $\ln (I_o-I_b)/(I_i-I_b)$, since this quantity is proportional to the absorption coefficient.

PLATE IV

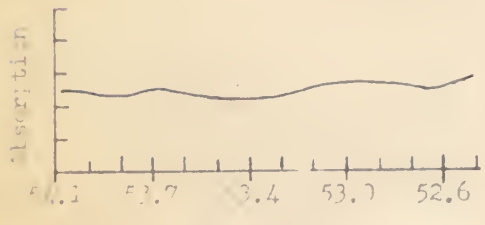
AG



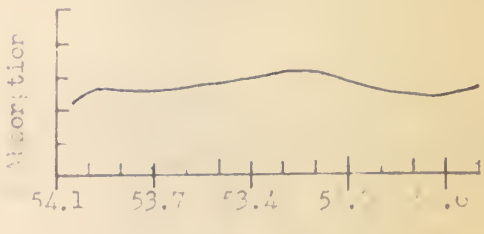
SR



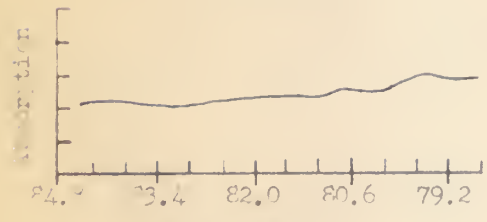
RB



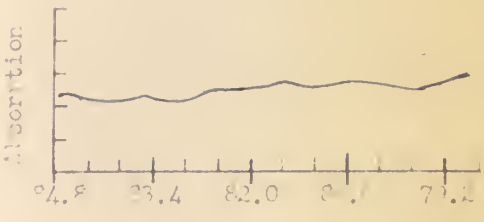
SR



RB



SR



RESULTS

The absorption curves shown in Plate IV indicate that no resonance absorption occurred.

DISCUSSION OF RESULTS

Statistical probable errors in the experiment were kept to less than one percent. However, fluctuations in the output of the x-ray unit were observed to cause as great as two percent deviations. In the event that absorption other than mass absorptions was indicated by the results, sufficient additional readings were taken at the same wave lengths to dispel errors due to machine behaviour.

If one accepts one percent error as the limit of the above experiment, such as to say that if nuclear resonance absorption exists, its magnitude must be less than one percent of the total absorption; then one may set an upper limit on the cross section for the reaction. For the nuclei considered the cross section for nuclear resonance absorption was less than 50 barns.

The metastable levels of silver are thought to have spins of 9/2, with a spin of 1/2 for the ground state (Plate I). Thus $|\Delta I| = 4$ or 5, with $|\Delta I| = 4$ being the most probable transition. Reference to Table 2 shows that such a transition would be electric octopole or possibly magnetic octopole. It was to

be expected, then, that any absorption would be small in the case of silver.

The half-lives of rubidium and strontium are so short as to not have been measured. These transitions, if observed, should have been more nearly dipolar in nature with a relatively higher probability of occurrence than for silver.

CONCLUSION

In conclusion, it may be said that, within the limits of experimental error, this investigation gave no indication of nuclear resonance absorption.

ACKNOWLEDGMENT

Appreciation is expressed to Dr. R. H. McFarland, Department of Physics, for his advice and constructive criticism during this investigation and the preparation of this manuscript. Gratitude is also expressed to Dr. A. B. Cardwell, Head of the Department of Physics.

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The types of processes by which nuclei may be excited upon irradiation with gamma rays are reviewed. An equation for probability of gamma ray transitions is indicated, along with a tabulation of approximate mean lives for gamma emission. In addition, a table is given which shows lowest allowed multipolar order for transitions involving a given spin change and parity change.

Nuclear states having a "measurably great" mean lifetime against gamma emission are termed metastable. Both this metastable state and the ground state of the same nuclide are termed isomers. A brief summary is given of work done by Wiedenbeck in which use was made of this metastable state in the study of absorption of high energy x-rays.

In no instance had any previous attempt been made to observe the nuclear resonance absorption of low energy x-rays. Many elements, Co^{60m}, Se^{75}, Br^{80m}, Rb^{87}, Sr^{87}, Tc^{94m}, Pb^{100}, Ag^{109m}, and Sn^{113}, exhibit transitions involving gamma rays of 100 kev. or less. These were of particular interest in that conventional x-ray equipment could be used in the investigation of possible resonant transitions. Of the above elements, Ag, Rb, and Sr were readily available; and since they represented different mean lifetime groups, were chosen for this experiment.

Each of these three metals was investigated over the appropriate energy ranges by using it as an absorber in a beam of

homogeneous x-rays. The procedure was to search for an indication of any resonance absorption of energy which might occur when these metals were placed in the x-ray beam as absorbers. A Pickering x-ray machine was the photon source. The various energies of beams required for the experiment were selected by means of a Bragg spectrometer. A measure of intensity of the beam with and without the absorber was obtained by using a Geiger tube with Berkeley scaler.

Following this, plots were made of absorption versus energy. These should show discontinuities at energies where resonance absorption had occurred. The plots gave no indication of discontinuities. Therefore, it was concluded that, within the limits of accuracy of this experiment, no resonance absorption had occurred.

It was estimated that experimental error was kept to less than one percent. From this it is possible to set an upper limit on the cross section for the reaction. In this investigation the cross section for nuclear resonance absorption was less than fifty barns.